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MECHANICAL PROPERTIES OF ALUMINUM ALLOY-GRAPHITE FIBER COMPOSITES

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Recent advances in fabrication techniques and the availability of relatively large amounts of material have made possible a somewhat extensive effort in property determination. In this report, the progress is summarized that has been made on optimizing the mechanical properties of aluminum-graphite composites consolidated by liquid-phase hot pressing. Various matrix alloys, fabrication parameters, fiber fractions, and lay-up geometries are considered. The properties investigated include: tensile, compressive, and flexture strength; modulus; and fatigue.

Approved

W. C. Riley, Director
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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Ronald C. Lawson, 2nd Lt, USAF
Technology Development Division
Deputy for Technology

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I. INTRODUCTION

Aluminum alloy matrix-graphite fiber composite materials are presently being developed for various applications that require high specific strength for temperatures up to 900°F (750K).

One of the most promising techniques for producing metal matrix-graphite fiber composites is by liquid-metal infiltration of a multifilament fiber bundle. By this process, composite wire is produced that has a diameter that depends upon the number of fibers in the initial bundle. For instance, Thornel 50, which is a rayon-based, 8-strand yarn that consists of 11,520 filaments, has a final wire diameter of 0.06 in. (approximately 1.5 mm). These wires can be consolidated into structural shapes by various processes, including diffusion bonding, liquid-phase hot pressing, sintering, and brazing. The technology of consolidation has been advanced to a point where the fabrication of relatively large structural shapes can be achieved. Examples of fabricated shapes are shown in Figs. 1 through 4, including a 0.25-in. (~ 6.4 mm) plate (Fig. 1), a 0.75-in. (19-mm) thick bar (Fig. 2), 10-in. (254 mm) square panels (Fig. 3), and angles (Fig. 4).

The mechanical properties of the composite wire have been obtained consistently in the range predicted by the rule of mixtures (ROM). However, the attainment of rule-of-mixtures properties for consolidated wire has been less frequent. The properties of consolidated composites depend upon the fabrication parameters of both the infiltration and consolidation processes. For example, increasing the rate at which the fiber is drawn through the molten aluminum bath (draw rate) can increase the strength of the final consolidated composite by 25 percent.

The most successful consolidation technique developed thus far is liquid-phase hot pressing in which wires are bonded under pressure at temperatures above the solidus in the two-phase, solid-liquid state. Extensive

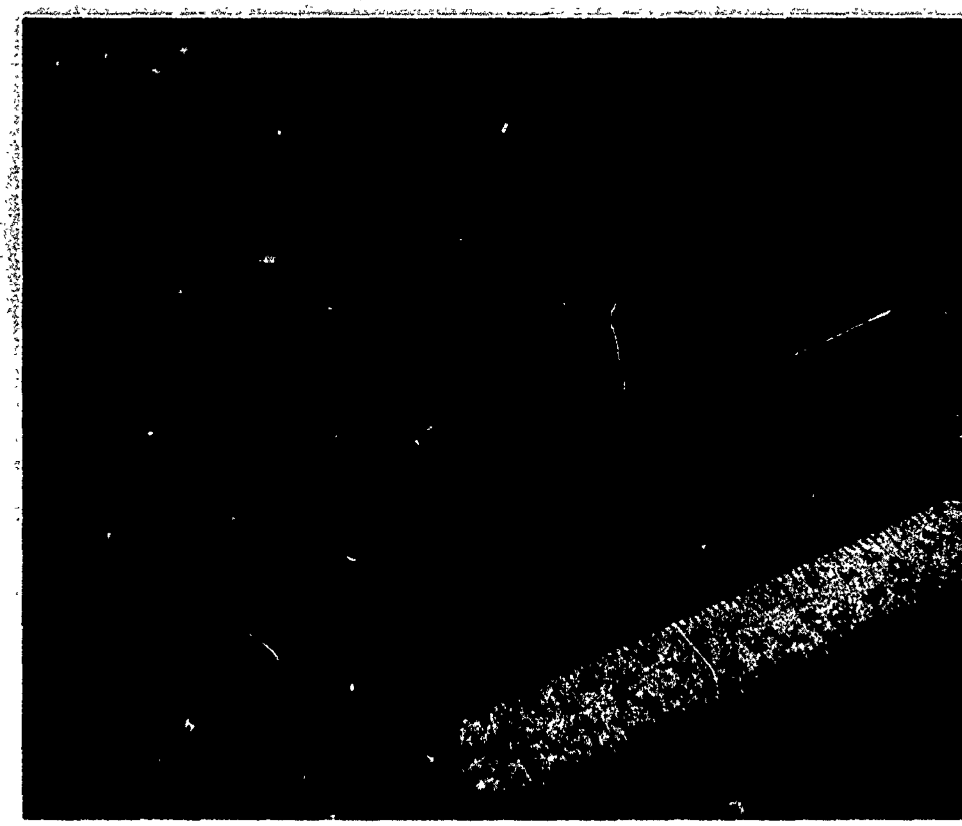


Fig. 1. Aluminum Graphite Plate 0.25-in. (6.4 mm) Thick

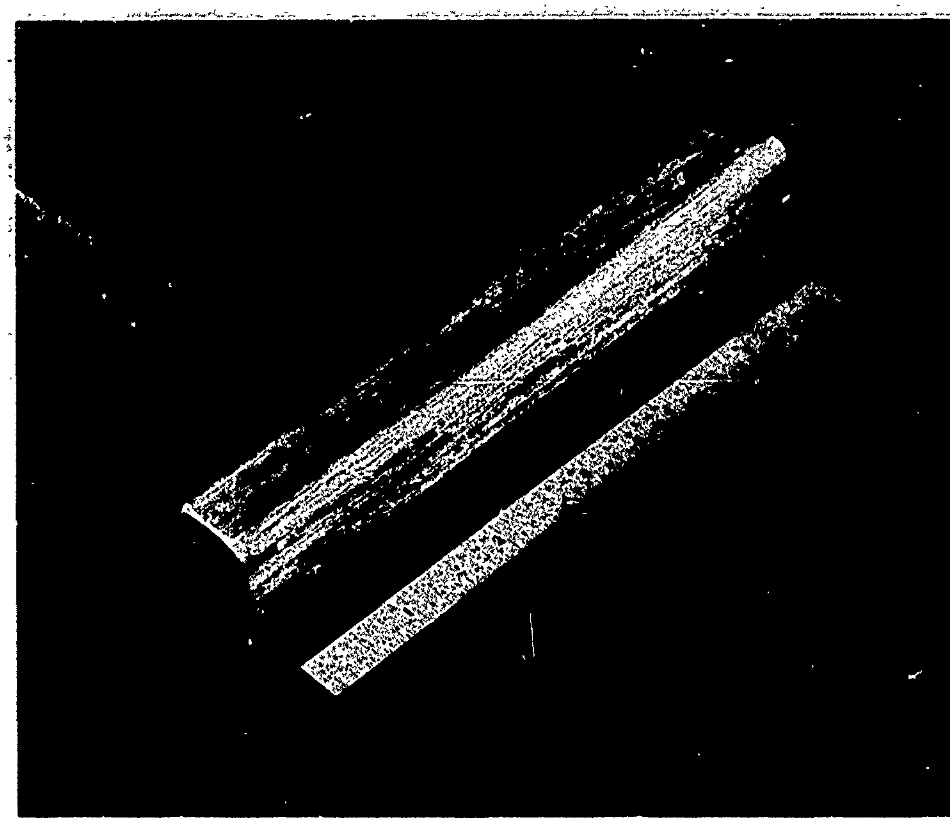


Fig. 2. Aluminum Graphite Bar 0.75-in. (19 mm) Square

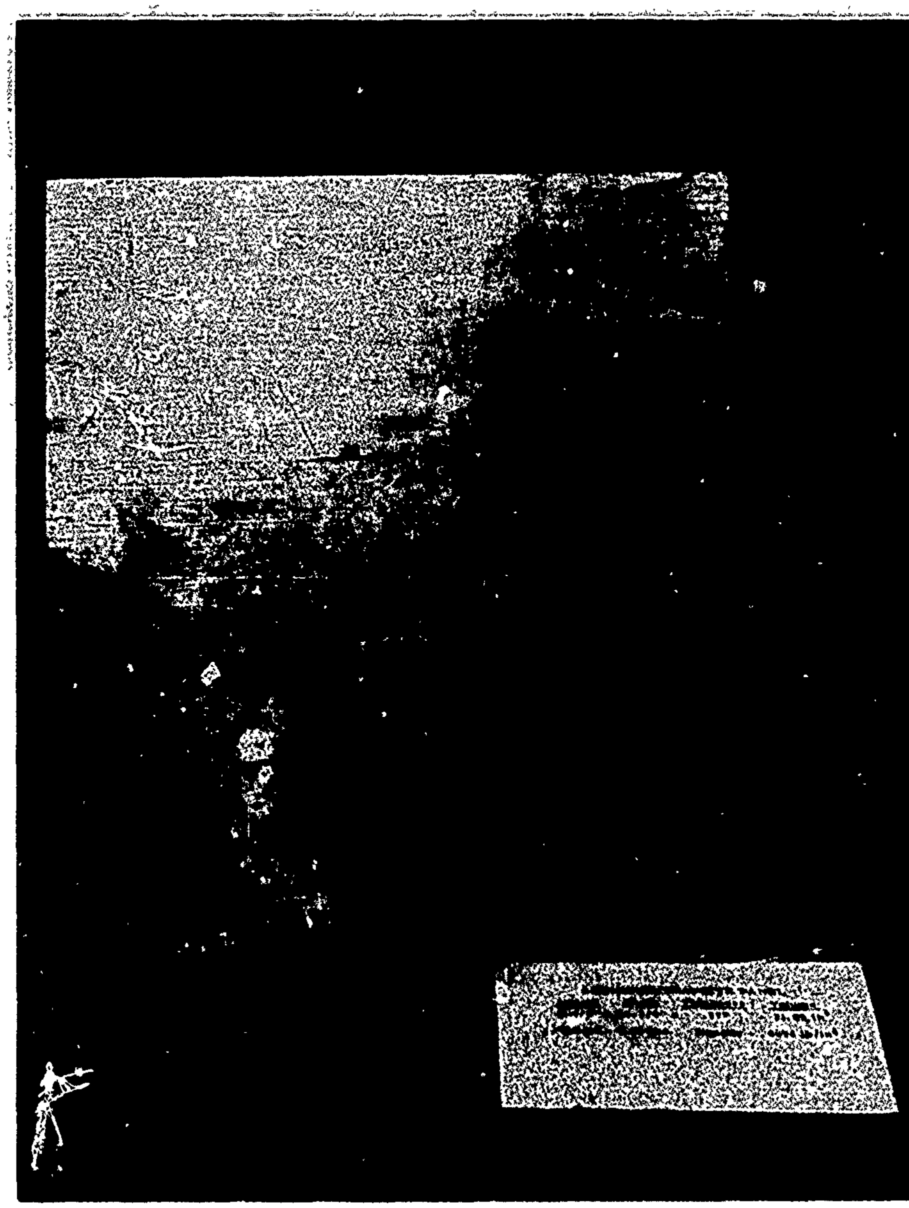


Fig. 3. Aluminum Graphite Panel 10-in. (254 mm) Square

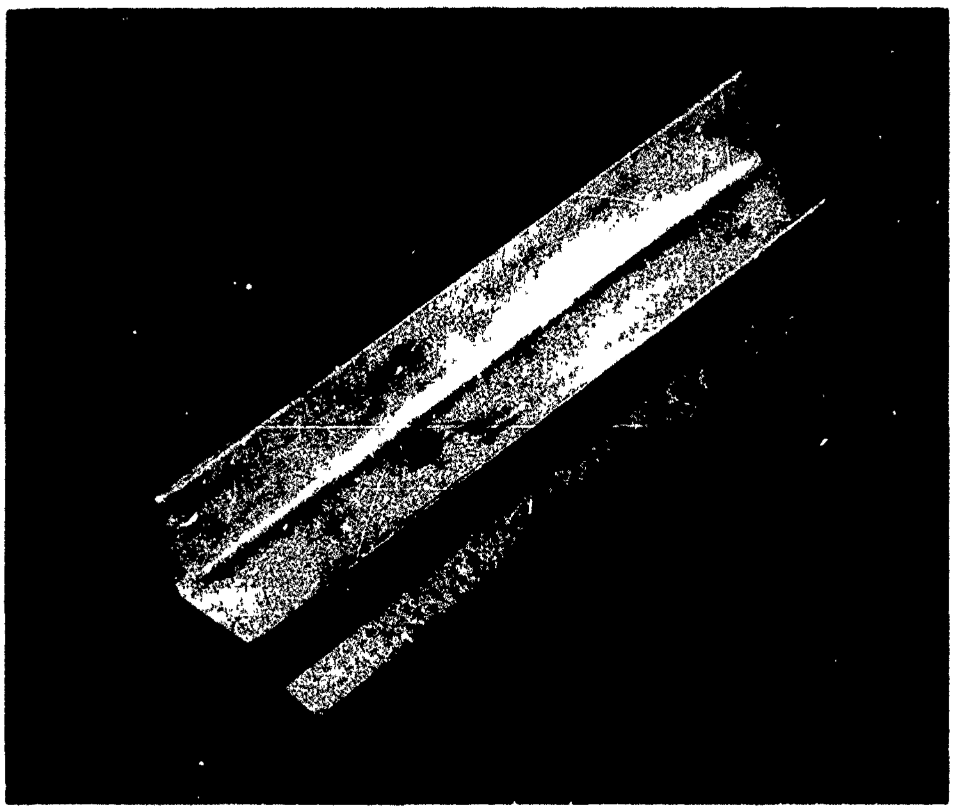


Fig. 4. Cross-Ply Reinforced 90-deg Angle of Aluminum Graphite

studies have been conducted at The Aerospace Corporation[1] and elsewhere[2] to optimize the temperature, pressure, and time parameters for this consolidation technique. Increasing the temperature of the pressing results in increased amounts of liquid phase and, hence, less mechanical damage to the fibers. Lowering the pressing temperature decreases the extent of fiber-matrix interaction and, hence, decreases chemical damage to the fibers. Moreover, with higher pressing temperatures, greater amounts of metal are expelled from between the fibers, thereby increasing the volume fraction of fibers in the composite.

In this investigation, the mechanical properties of composite materials processed by two techniques have been examined. Technique A is a shorter time, higher temperature, lower pressure process, while Technique D is a longer time, lower temperature, and higher pressure process. In addition to the effects of time, temperature, and pressure, the impact of aluminum alloy foils (fillers) utilized in the consolidation methods must be considered. The foils are inserted between planes of wire to provide a uniform load distribution among the wires during pressing, thereby minimizing mechanical damage to the fibers.

[1] W. C. Harrigan, Jr., Fabrication of Aluminum-Graphite Composite, TR-0074(9250-03)-2, The Aerospace Corporation, El Segundo, Calif. (to be published).

[2] R. T. Pepper, R. A. Penty, and S. J. Allen, "Fabrication of Aluminum-Graphite Composites," J. Composite Mater., 8, 29-37 (1974).

II. MATERIALS

Various wrought and cast aluminum alloys have been used to make aluminum-graphite composites including the 2000, 5000, 6000, and 7000 series of wrought alloys. In this work, one wrought composition (6061) and two cast compositions (201 and 202) were selected for property determination since a considerable number of consolidation studies have been performed with these alloys. Filler foil materials used in the present work include the 6061, 2024, 5056, and 356 alloys. The nominal compositions of these alloys are listed in Table 1. The graphite fiber in all the composites studied was Union Carbide Corporation's grade Thornel 50 8-strand yarn. Parameters of the liquid-phase, hot-pressing consolidation Techniques A and D are listed in Table 2. Technique A was performed in-house, and Technique D was performed by DWA Composite Specialties, Inc.

The composite materials used in this program are listed in Table 3 along with the pertinent matrix alloy, filler alloy (if any), volume fraction of fiber, consolidation method, wire lay up, and form and size of the final product. A variety of composites was studied that contained fiber fractions ranging from 22 to 34 percent and had two cross-ply wire, lay-up geometries. The final forms of the consolidated composite were 0.25-in. (6.4 mm) thick square bars and 0.25-in. (6.4 mm) thick plates. The precursor wire properties of these composites are given in Table 4.

Table 1. Composition of Aluminum Alloys Used in Fabricated Aluminum-Graphite Composites

Alloy	Use	Nominal Composition, wt%							
		Si	Cu	Mn	Mg	Cr	Ti	Ag	Fe
201	Matrix	0.1	4.6	0.4	0.4		0.3	0.7	0.1
202	Matrix	0.1	4.6	0.5	0.4	0.4	0.3	0.7	0.1
6061	Matrix, Filler	0.6	0.3		1.0	0.2			
2024	Filler		4.4	0.6	1.5				
5056	Filler			0.1	5.1	0.1			
356	Filler	7.0			0.4				

Table 2. Consolidation Techniques Used to Produce Aluminum-Graphite Composite Structures

Technique[a]	Pressing Temperature,[b] °C (°K)	Pressure, psi (MPa)	Time, min
A	605-615 (878-888)	400 (2.75)	15
D	560-580 (833-853)	4000 (27.5)	40

[a]Method D was developed by DWA Composite Specialties, Inc., Los Angeles, California

[b]Actual temperature of pressing is determined by composition of matrix.

Table 3. Aluminum Alloy-Thornel 50 Graphite Composition Material Used in Property Study

Material No.	Fraction Fiber, vol %	Matrix Alloy	Fabrication				Filler Foil Composition
			Technique[a]	Lay up[b]	Form	Size, in.	
1	31	201	A	U	Bar	0.25 × 0.25 × 4	None
2	26	201	A	U	Bar	0.25 × 0.25 × 4	None
3	32	201	D	U	Plate	4 × 4 × 0.25	None
4	24	201	D	U	Plate	4 × 4 × 0.25	2024
5	[illegible]2	202	A	U	Bar	0.25 × 0.25 × 4	None
6	30	202	A	X1	Plate	2 × 2 × 0.25	2024
7	28	202	D	U	Plate	4 × 4 × 0.25	2024
8	28	202	D	X2	Plate	4 × 4 × 0.25	5056
9	29	6061	A	U	Bar	0.25 × 0.25 × 4	None
10	34	6061	A	U	Bar	0.25 × 0.25 × 4	356
11	23	6061	D	U	Plate	4 × 4 × 0.25	2024

[a] See Table 2

[b] U = unidirectional lay up, X1 = cross ply 0-90-0-90 deg, X2 = cross ply 0-90-0 deg

Table 4. Precursor Wire Properties

Material No.	Fraction Fiber, vol %	Draw Rate of Wire During Production, in./min (mm/sec)	Source of Wire	Tensile Strength of Wire, ksi (MPa)
1	28	12 (5)	Aerospace	100.5 (693)
2	24		Fiber Materials, Inc.	88.0 (607)
3	28	12-16 (5-7)	Aerospace	100.5 (693)
4	24		Fiber Materials, Inc.	88.0 (607)
5	28	12 (5)	Aerospace	110.0 (758)
6	28	12-16 (5-7)	Aerospace	110.0 (758)
7	28	12-16 (5-7)	Aerospace	110.0 (758)
8	28	12-16 (5-7)	Aerospace	110.0 (758)
9	28	3 (1-0.25)	Aerospace	100.0 (690)
10	28	3 (1-0.25)	Aerospace	100.0 (690)
11	30	12-16 (5-7)	Aerospace	105.0 (724)

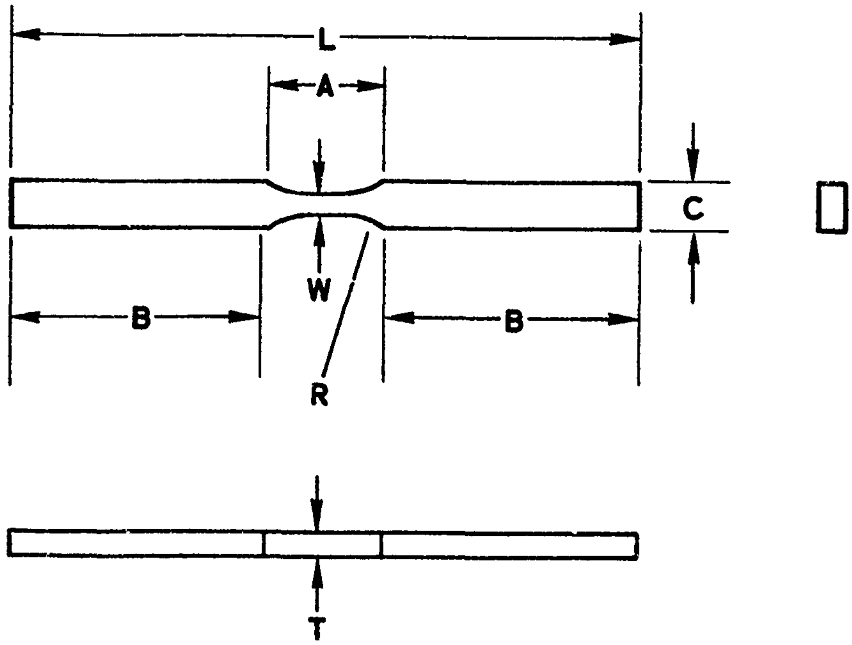
III. TEST METHODS

Tensile tests were performed on 4-in. (100 mm) long specimens machined to the configuration shown in Fig. 5. Aluminum alloy tabs were adhesively bonded to the grip ends to prevent damage to the fibers from the loading grips. Testing was performed on an Instron tensile machine with 0.02 in./min (0.5 mm/min) cross-head speed. A 0.5-in. (12.7 mm) gauge length strain extensometer was used to measure strain in the specimen.

Compression tests were performed on specimens machined into the form of a right cylinder 0.853 in. (21.7 mm) long and 0.207 in. (5.26 mm) in diameter. Prior to placing it in the compression fixture, the ends of the specimen were lubricated with graphite powder. The cross-head speed was between 0.01 and 0.05 in./min (0.25 and 1.27 mm/min).

The dynamic modulus was measured on samples ranging in size from 0.6 to 4 in. (15 to 102 mm). Straight-beam, quartz-crystal transducers with a characteristic frequency of 3 MHz were used in the tests. A drop of mineral oil was used on the transmitting and receiving transducer crystals to make intimate contact with the sample that was placed between them on a spring-loaded optical bench stand. A 50-V output pulse of a pulse generator was applied to the transmitting crystal as well as to the sweep trigger input of an oscilloscope. The time of arrival of the first pulse was used to measure the velocity of the wave through the specimen and, from this measurement, the dynamic Young's modulus was determined.

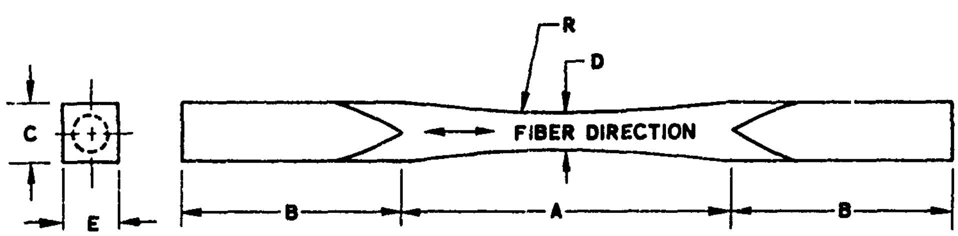
Flexure properties of composite materials were determined on three- and four-point bend specimens 2.75 in. (69.9 mm) long (overall) and 0.5 in. (12.7 mm) wide. Beam depths of either 0.09 in. (2.3 mm) or 0.06 in. (1.5 mm) were used. The support span was 1.5 in. (38.1 mm), and the load span for the four-point tests was 0.5 in. (12.7 mm). Both the specimens and the test procedures were in conformance with Test Specification ASTM D709-71 for flexural properties of plastics. The specimens were tested at the recommended cross-head speed of 0.05 in./min (1.27 mm/min).



	in.	mm
W = WIDTH	0.125	3.175
T = THICKNESS	0.200	5.10
L = OVERALL LENGTH	3.50-4.0	90-100
A = LENGTH OF REDUCED SECTION	0.75	19
R = RADIUS OF FILLET	0.375	10
B = GRIP SECTION (tab length)	1.50	38
C = WIDTH OF GRIP SECTION	0.25	6

Fig. 5. Composite Tensile Specimen

Fatigue behavior was measured at room temperature on the smooth hourglass cross-section specimens illustrated in Fig. 6. The grip ends of the specimens have a rectangular cross section to permit compression gripping. With the use of contact cement, the relatively short grip sections were coated with silicon carbide powders to enhance the gripping. Testing was performed on a closed-loop, electrohydraulic fatigue machine under load control and with a sinusoidal waveform at 10 Hz. Total separation of the specimen was the criterion for fatigue life.



		in.	mm
A	LENGTH OF REDUCED SECTION	1.48	37.6
B	GRIP SECTION LENGTH	1.0	25.4
C	WIDTH OF GRIP SECTION	0.2	5.1
D	MINIMUM CROSS SECTION DIAMETER	0.148	3.8
E	THICKNESS OF GRIP SECTION	0.240	6.1
R	RADIUS	6.0	152.4

Fig. 6. Composite Fatigue Specimen

IV. RESULTS AND DISCUSSION

A. TENSILE AND MODULUS BEHAVIOR

The tensile strength and Young's modulus of various aluminum-graphite composite materials are shown in Table 5. The materials identified by number are those identified similarly in Table 3. The two processing methods compared in Table 5 are the higher temperature Technique A and the lower temperature Technique D described in Table 2. Although the higher fiber-fraction 201 and 202 matrix composites produced by the higher temperature technique (A) were assumed to result in higher strength products on the basis of the rule-of-mixtures predicted strength (compare Materials No. 1 and 3, and 5 and 7), the lower volume fiber-fraction material and the cross-ply material show the opposite to be true (Materials No. 2 and 4, and 6 and 8, respectively). The efficiency of consolidation, as measured by the strength as a percentage of the precursor wire strength, also appears to be greater for the higher temperature method in the 6061 as well as 201 and 202 matrix, higher fiber-fraction composites, but similar efficiencies are indicated for the lower fiber-fraction and cross-ply composites. It can be tentatively concluded, therefore, that both methods are potentially efficient for consolidating wires. These observations must be tempered by the fact that some of these comparisons were made between materials with different fiber fractions and different filler alloys or between materials with and without filler foils. The characterization of these effects has not been completed, but information available at the present time does not confirm any strong trend of consolidation efficiency with fiber fraction.

The effect of filler foil on consolidation efficiency is also not yet clear. A comparison of Materials No. 2 and 4 indicates a similar consolidation efficiency for composites with and without filler foils, while a comparison of Materials No. 9 and 10 shows that a greater consolidation efficiency was experienced with the material that was without the filler foil. Both cross-ply

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Table 5. Tensile Properties of Various Aluminum-Graphite Composite Materials

Material No.	Alloy	Technique	Fiber, vol %	Al_4C_3 Content, ppm	Tensile Strength, ksi (MPa)	Tensile Strength, % ROM	Young's Modulus, Msi (GPa)	Young's Modulus, % ROM	Tensile Strength, % Wire Strength
1	201	A	31	500	87.5 (603)	88	23.5 (162)	96	87
3	201	D	32	350	73.5 (507)	72	22.3 (154)	89	73
2	201[a]	A	26	411	71.8 (495)	83	19.7 (136)	89	82
4	201[a]	D[c]	24	349	70.5 (486)	87	18.6 (128)	87	80
5	202	A	32	185	100.0 (690)	98	25.4 (175)	101	91
7	202	D[c]	28	214	82.0 (565)	89	23.7 (163)	102	74
6	202[b]	A[c]	30	538	33.2 (229)	69	11.2 (77)	93	61
8	202[b]	D[c]	28	550	45.5 (314)	75	16.5 (114)	107	62
9	6061	A	29	372	87.8 (605)	93	22.4 (154)	95	88
11	6061	D[c]	23	-	72-80 (496-552)	91-100	22.0 (152)	106	69-76
10	6061	A[c]	34	805	78.6 (542)	73.4	22.7 (157)	87.4	79

[a] Lower fiber fraction starting wire

[b] Cross-ply lay ups

[c] Filler foil used. See Table 3 for compositions.

composites (Materials No. 6 and 8) had a significantly lower consolidation efficiency than the unidirectional composites.

The relationship between the tensile properties of the composite wire and those of the hot-pressed, consolidated composite is shown in Fig. 7 for the matrix aluminum alloy 201. Two ranges of initial fiber-fraction wire are represented. The higher fiber-fraction wire consisted of 28- to 30-percent fiber, and the tensile properties ranged from 90 ksi (620 MPa) to 115 ksi (795 MPa). The lower fiber-fraction wire was between 22- and 26-percent fiber, and the strength ranged from 80 ksi (550 MPa) to 95 ksi (655 MPa). Both groups of fibers appear to possess strengths at least as high as were predicted by the rule of mixtures. The individual data points in Fig. 7 are for a variety of processing conditions. These data points are represented by open circles for bars or sheet consolidated from lower fiber-fraction wire and solid circles for bars and sheet consolidated from higher fiber-fraction wire. It is significant that the strengths of the consolidated wire fall consistently below those of the precursor wire, although most processes result in strengths close to the lower bound of the range predicted by the rule of mixtures. Increasing the volume fraction during consolidation results in a decrease in the strength as predicted by the rule of mixtures, although not necessarily a decrease in the absolute strength.

B. COMPRESSIVE AND TRANSVERSE TENSILE PROPERTIES

The compressive properties of 201, 202, and 6061 aluminum matrix-graphite fiber composite materials are presented in Table 6. Except for the 6061 matrix composite, the compressive strengths of these materials are within 10 percent of the tensile strengths. Results of experiments on other aluminum-graphite composites indicate that very high compressive strengths can be obtained if extensive carbide formation is permitted. Compressive strengths as high as 185 ksi (1276 MPa) have been produced by such methods, but a considerable sacrifice of tensile properties was entailed. The high compressive strength of the 202 alloy composite (Material No. 5) was accompanied by one of the lowest carbide contents (185 ppm) found among these

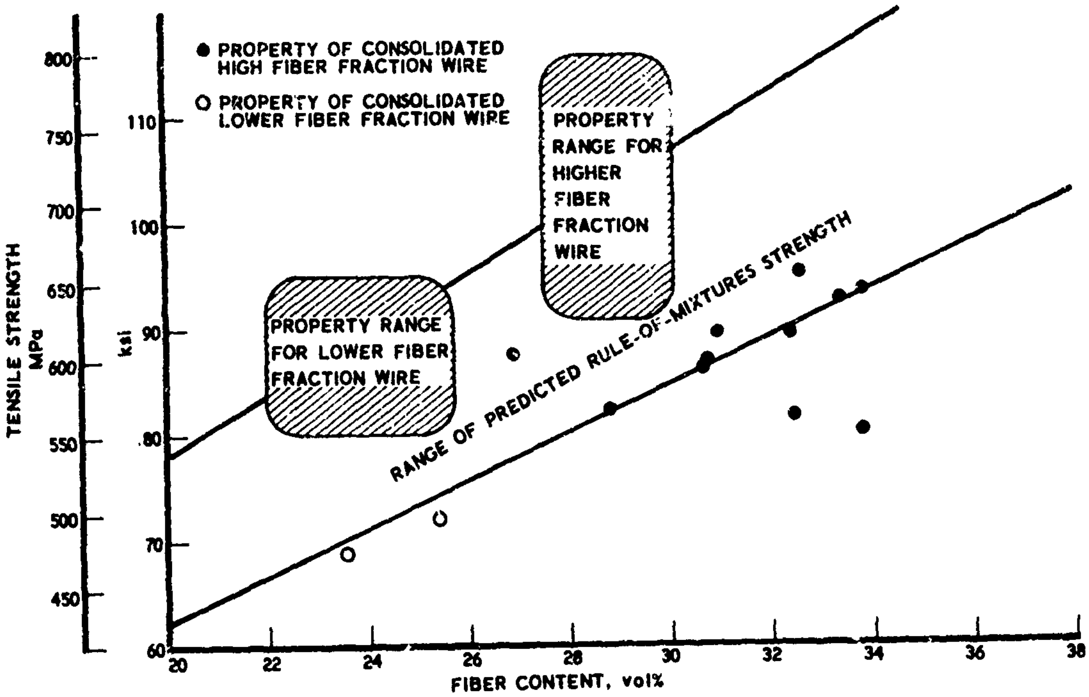

Fig. 7. Tensile Strength of 201 Aluminum Alloy and Thornel 50 Graphite Fiber for Various Volume Fractions of Fiber and Processing Treatments

Table 6. Compressive Properties of Various Aluminum-Graphite Composite Materials

Material No.	Matrix Alloy	Compressive Failure Stress, ksi (MPa)	Compressive Young's Modulus, Msi (GPa)
1	201	78-89 (538-614)	25-27 (172-186)
2	201	60-66 (414-455)	19.1-22.3 (132-154)
3	201	76.5 (527)	19.1 (132)
5	201	81.0 (559)	21.8 (150)
9	6061	58-61 (400-421)	19-23 (131-159)

composites and, hence, some degree of matrix-fiber bonding rather than carbide formation is the apparent reason for such encouraging results. High compressive strength is not necessarily accompanied by high compressive modulus. The tensile modulus of Material No. 5 is 25 Msi (172 GPa), while the compressive modulus is only 19 Msi (132 GPa). The 201 matrix-alloy composite (Material No. 1), conversely, had a slightly higher compressive modulus than tensile modulus.

Transverse tensile properties were determined on two matrix-alloy composites, and the results are summarized in Table 7. For unidirectional fiber orientations, transverse tensile strengths for both the 201 and 202 matrix-alloy composites are 4.5 ksi (31 MPa). These values are approximately one-fourth of the expected values and indicate that, although some degree of fiber-matrix adhesion has been achieved, this property is not yet optimized for these composites. Even the cross-ply composites result in less than optimum transverse tensile strength. Further improvements in fiber-matrix adhesion are required before optimum compressive and transverse tensile properties are achieved in these composites.

C. FATIGUE BEHAVIOR

The fatigue behavior of two aluminum-graphite composite materials was determined over a range of cycle life from 10^1 to 10^8 to establish the stress-life behavior (S/N) curve and the mechanism of fatigue. The materials studied were No. 7 and 9, which represented the 201 and 6061 matrix-alloy composites, respectively. A summary of the fatigue results is given in Table 8. Fatigue ratios examined ranged from 0.5 to 0.85 for the 6061 matrix material and from 0.5 to 0.90 for the 202 matrix material. Fatigue strength (stress for 10^7 cycle life) is above 50 percent of the fracture strength for both composites. The S/N behavior of these materials is compared in Fig. 8 with other composite fatigue data reported in the literature, including

Table 7. Transverse Properties of Various Alumirum-Graphite Composite Materials

Material No.	Matrix Alloy	Transverse Failure Stress, ksi (MPa)	Transverse Modulus, Msi (GPa)
3	201	4.5 (31)	
4	201	4.5 (31)	
6	202[a]	33.2 (229)	11.2 (77)
7	202	4.4 (30)	
8	202[b]	17.0 (117)	8.8 (61)

[a] X2 lay up 0-90-0-90 deg

[b] X1 lay up 0-90-0 deg

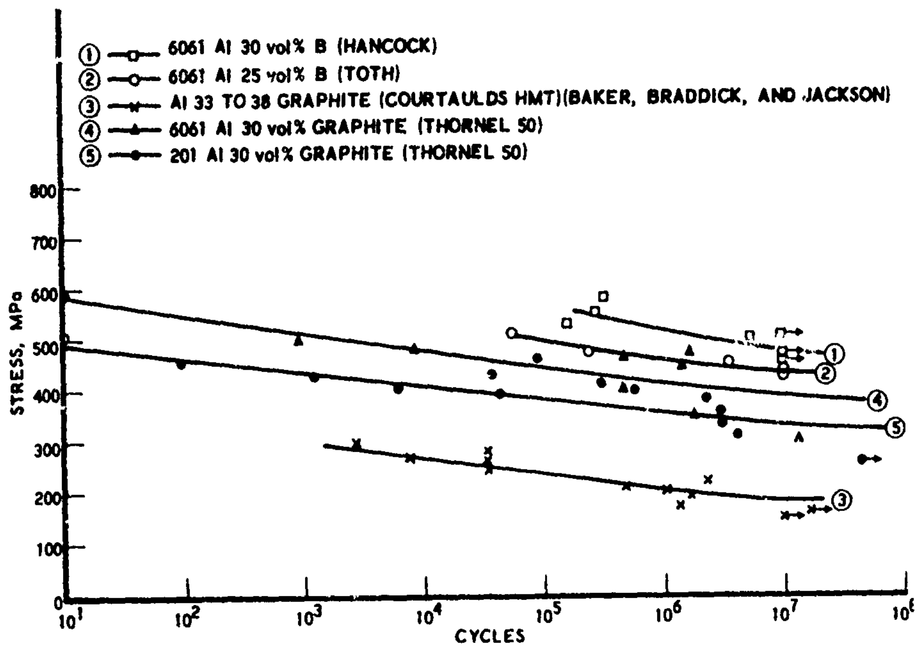

Fig. 8. Fatigue Behavior of Aluminum-Graphite Composites Compared with Aluminum-Boron Composites

Table 8. Summary of Fatigue Properties of Two Aluminum-Graphite Composite Materials

Material No.	Matrix Alloy	Fatigue Stress, ksi (MPa)	Fatigue Ratio σ/σ_u	Life Cycles
7	202	37 (254)	0.45	9.9×10^7
7	202	44 (305)	0.54	4.2×10^6
7	202	48 (330)	0.59	3.1×10^6
7	202	52 (356)	0.63	2.9×10^6
7	202	55 (381)	0.67	2.2×10^6
7	202	57 (393)	0.70	4.1×10^4
7	202	57 (393)	0.70	5.9×10^5
7	202	59 (406)	0.72	6.0×10^3
7	202	59 (407)	0.72	3.0×10^5
7	202	63 (432)	0.77	1.1×10^3
7	202	63 (432)	0.77	3.7×10^4
7	202	66 (457)	0.80	6.0×10^1
7	202	66 (457)	0.80	8.7×10^4
9	6061	44 (300)	0.51	1.4×10^7
9	6061	51 (352)	0.60	1.7×10^6
9	6061	58 (400)	0.68	4.6×10^5
9	6061	64 (440)	0.75	1.3×10^6
9	6061	67 (460)	0.79	4.8×10^5
9	6061	68 (470)	0.80	1.5×10^6
9	6061	70 (480)	0.82	8.5×10^3
9	6061	73 (500)	0.85	9.3×10^2

6061 aluminum-30 vol% boron,[3] 6061 aluminum-25 vol% boron,[4] and aluminum-graphite[5] composites prepared by chemical vapor deposition (CVD). The S/N curves for all aluminum composites compared are more or less parallel in the range from 10^5 to 10^7 cycles. Fatigue strength of the 6061 matrix composite is 13 percent greater than the 201 matrix composite and 50 percent greater than the CVD composite, but 20 percent below the 30 vol% boron fiber composite.

The range of scatter in the 6061 matrix composite is considerable in the high cycle area. In this range, a number of 6061 specimens failed at stresses comparable to those withstood by the aluminum-boron composites. This scatter can be attributed partially to the fact that the minimum cross section of the specimen helped to confine the fracture to a more restricted section of the specimen length. However, since all fractures were not confined to the minimum cross section, a large variation in fatigue strength seems to have existed along the reduced area of the specimen. It appears, from scanning electron microscopy on the failed specimen, that the fatigued portion of the specimen is more prevalent in areas consisting primarily of matrix material, while the tensile overload region consists of both fiber and matrix regions. In specimens where the fatigue area appears to be in a region of fibers, the fatigued surface is usually near a void in the matrix.

D. FLEXURE PROPERTIES

Several plates of 201 matrix-alloy composite that measured 4 × 4 × 0.25 in. (102 × 102 × 6 mm) were fabricated by Technique D with lower fiber-fraction wires. These plates would be similar to Material No. 4 of

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[3] J. R. Hancock, Fatigue of Boron-Aluminum Composites, AFML-TR-72-113, Air Force Materials Laboratory (November 1972).

[4] I. J Toth and K. D. Shimmin, "Fatigue and Fracture of Metal-Matrix Composites," Proceedings of Air Force Conference on Fatigue and Fracture of Aircraft Structure and Materials, AFFDL-TR-70-144, Air Force Flight Dynamics Laboratory, (1970), pp. 343-376.

[5] A. A. Baker, D. M. Braddick, and P. W. Jackson, "Fatigue of Boron-Aluminum and Carbon-Aluminum Fibre Composites," J. Mater. Sci. 7, 747 (1972).

Table 3, but with variations in foil composition and pressing pressures. Materials No. 12 and 14 contained 6061 and 5056 filler foil, respectively, rather than the 2024 alloy, and Material No. 15 was pressed at 2500 psi (17.2 MPa) rather than the standard 4000 psi (27.6 MPa). The results of an average of two to four individual flexure tests are shown in Table 9. Neither the filler alloy nor the carbide content appears to result in any unusual variation in flexure strength. The plate fabricated with 6061 filler alloy did, however, have about a 10-ksi (69 MPa) lower tensile strength. The flexure strengths of these plates are about 1.3 times the tensile strengths, and the flexure modulus is about 0.8 times the tensile modulus. Interlamellar shear might be responsible for the low flexure modulus properties of these plates.

E. DYNAMIC MODULUS

Young's modulus of composites, as determined by tensile testing, is subject to uncertainties arising from internal stresses introduced during fabrication. In the case of aluminum-graphite composites fabricated by liquid metal infiltration, the large difference in thermal expansion coefficients between the aluminum matrix and the graphite fiber presents a potential residual stress situation. The appearance of two distinct slopes during the initial elastic loading of some of these composites suggests that such residual stresses might indeed be present. The dual modulus attendant to certain composite materials seems to disappear after the initial elastic loading.

In order to eliminate any uncertainties in Young's modulus for these compositiies, dynamic modulus measurements have been made on a number of composite materials and compared with the static Young's modulus values determined by tensile testing. The results of this comparison are shown in Table 10 for both unidirectional and cross-ply composites. The modulus determined by both methods appears to be similar for the cross-ply, foil-modified Material No. 8 and the unidirectional Material No. 12. A 22-percent lower dynamic modulus than static modulus was measured in tests of the cross-ply unmodified Material No. 8. This discrepancy has not been explained.

Table 9. Flexure Properties of 201 Alloy Matrix Composite

Material No.	Filler Foil	Fiber Fraction Content, vol%	Al_4C_3 Content, ppm	Tensile Strength, ksi (MPa)	Young's Modulus, Msi (GPa)	Transverse Tensile Strength, ksi (MPa)	Flexure Strength, ksi (MPa)	Flexure Modulus, Msi (GPa)
12	6061	24.3	363	60 (144)	19.3 (133)	5.1 (35)	95 (655)	15.6 (108)
13	2024	26.8	340	71 (490)	27.6 (190)	4.5 (31)	102 (703)	18.9 (130)
14	5056	22.0	818	70 (483)	25.4 (175)	5.3 (37)	95 (655)	16.5 (113)
15	2024	23.5	595	71 (490)	23.2 (160)	4.6 (32)	96 (662)	17.2 (119)

Table 10. Dynamic Modulus of Aluminum Alloy-Graphite Composites

Material No.	Matrix Alloy	Lay up	Dynamic Modulus		Static Modulus	
			Longitudinal, Msi (GPa)	Transverse, Msi (GPa)	Longitudinal, Msi (GPa)	Transverse, Msi (GPa)
6	202	X2	11.2 (77)	11.7 (81)		
8	202	X1	12.7 (88)	9.1 (63)	16.5 (114)	8.8 (61)
8[a]	202	X1	15.5 (106)	8.8 (60)	14.7 (101)	8.5 (59)
12	201	U	18.7 (129)		19.3 (133)	

[a]Foil modified

V. CONCLUSIONS

The conclusions derived from this investigation are as follows:

1. Liquid-phase hot pressing can result in the consolidation of composite wires into structural shapes with tensile strengths as high as 90 percent of the original wire strength.

2. With the present consolidation techniques, there appear to be limits to the amount of increased strengthening that can be achieved by increasing the volume fraction of fibers by liquid expulsion during pressing.

3. Without sacrificing tensile properties, compressive strengths within 10 percent of tensile strengths can be achieved for aluminum-graphite composites consolidated by liquid-phase hot pressing.

4. At present, transverse tensile properties of aluminum-graphite composites are one-fourth as high as the expected values.

5. The fatigue strength of aluminum-graphite composites is above 50 percent of the tensile strength and within 20 percent of that for aluminum-boron composites.

LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space and missile systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Launch and reentry aerodynamics, heat transfer, reentry physics, chemical kinetics, structural mechanics, flight dynamics, atmospheric pollution, and high-power gas lasers.

Chemistry and Physics Laboratory: Atmospheric reactions and atmospheric optics, chemical reactions in polluted atmospheres, chemical reactions of excited species in rocket plumes, chemical thermodynamics, plasma and laser-induced reactions, laser chemistry, propulsion chemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, photosensitive materials and sensors, high precision laser ranging, and the application of physics and chemistry to problems of law enforcement and biomedicine.

Electronics Research Laboratory: Electromagnetic theory, devices, and propagation phenomena, including plasma electromagnetics; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, semiconducting, superconducting, and crystal device physics, optical and acoustical imaging; atmospheric pollution; millimeter wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; metal matrix composites and new forms of carbon; test and evaluation of graphite and ceramics in reentry; spacecraft materials and electronic components in nuclear weapons environment; application of fracture mechanics to stress corrosion and fatigue-induced fractures in structural metals.

Space Physics Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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